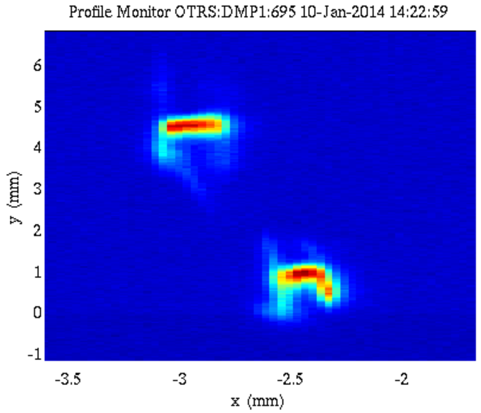
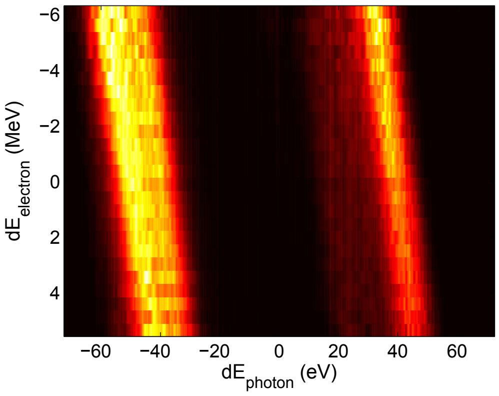




Twin-Bunch Two-Color X-rays at the Linac Coherent Light Source

Agostino Marinelli

SLAC

IPAC 2016

Busan, South Korea

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline of the Talk

1) Introduction

2) Single-bunch 2-color schemes

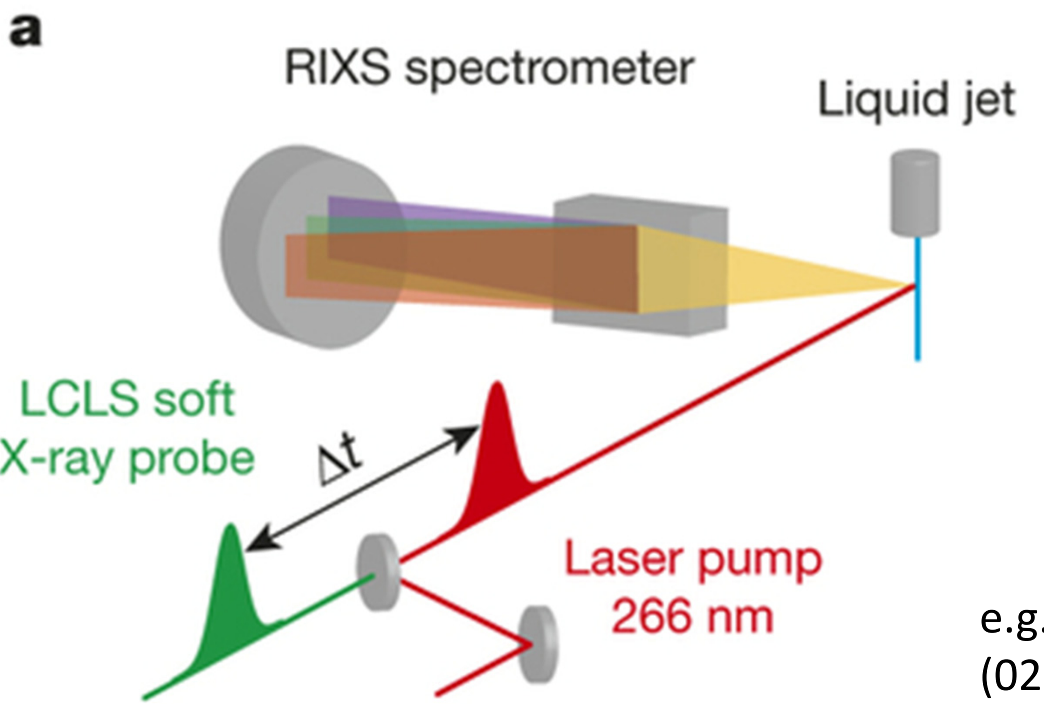
3) Twin-bunch FEL

4) Recent developments on 2 color generation

5) Conclusions

Pump/Probe Experiments with XFEL

Pump/probe experiments:
Excited sample with a pulse and probe it with a second pulse after controllable delay

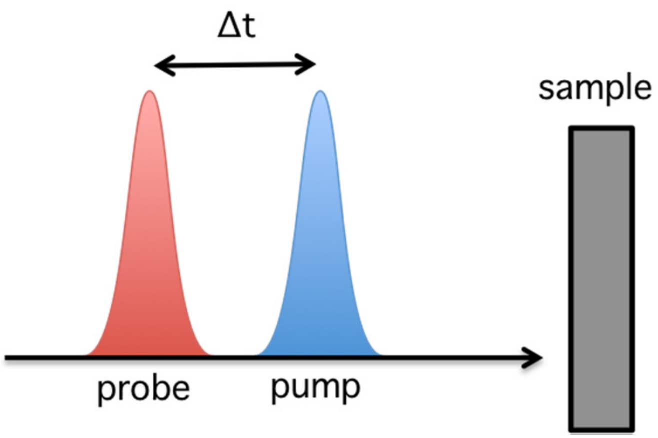


Time resolution given by shortest between

1) Pulse duration
2) Timing accuracy (jitter or stamping)

e.g. From: P. Wernet et al. Nature 520, 78–81 (02 April 2015) doi:10.1038/nature14296

2 Color Free-Electron Lasers



$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

2 x-ray pulses with

-tunable energy difference
-tunable arrival time

Used for applications that need high-photon energy pump!

PRL 110, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 13 December 2012; published 25 March 2013)

PRL 111, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

ARTICLE

Received 8 Sep 2013 | Accepted 12 Nov 2013 | Published 4 Dec 2013 DOI: 10.1038/ncomms3919

Two-colour hard X-ray free-electron laser with wide tunability

Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], Tadashi Togashi[2], Kazuaki Togawa[1], Kensuke Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

PRL 110, 064801 (2013) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2013

Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments

Giovanni De Ninno,[1,2] Benoît Mahieu,[1,2,3] Enrico Allaria,[2] Luca Giannessi,[2,4] and Simone Spampinati[2]

ARTICLE

Received 24 May 2013 | Accepted 21 Aug 2013 | Published 18 Sep 2013 DOI: 10.1038/ncomms3476 OPEN

Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser

E. Allaria[1], F. Bencivenga[1], R. Borghes[1], F. Capotondi[1], D. Castronovo[1], P. Charalambous[2], P. Cinquegrana[1],

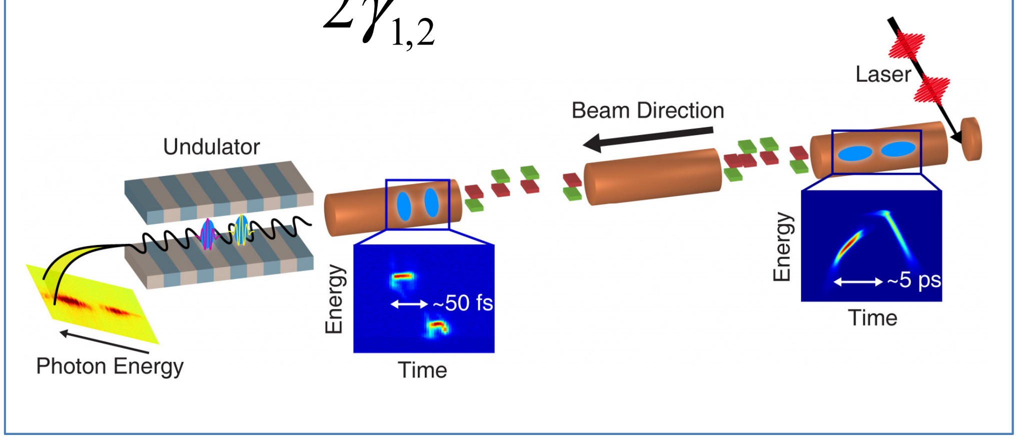
PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

V. Petrillo,[1] M. P. Anania,[2] M. Artioli,[3] A. Bacci,[1] M. Bellaveglia,[2] E. Chiadroni,[2] A. Cianchi,[4] F. Ciocci,[3] G. Dattoli,[3] D. Di Giovenale,[2] G. Di Pirro,[2] M. Ferrario,[2] G. Gatti,[2] L. Giannessi,[3] A. Mostacci,[5] P. Musumeci,[6] A. Petralia,[3] R. Pompili,[4] M. Quattromini,[3] J. V. Rau,[7] C. Ronsivalle,[3] A. R. Rossi,[1] E. Sabia,[3] C. Vaccarezza,[2] and F. Villa[2]

Two-Color FELs at LCLS

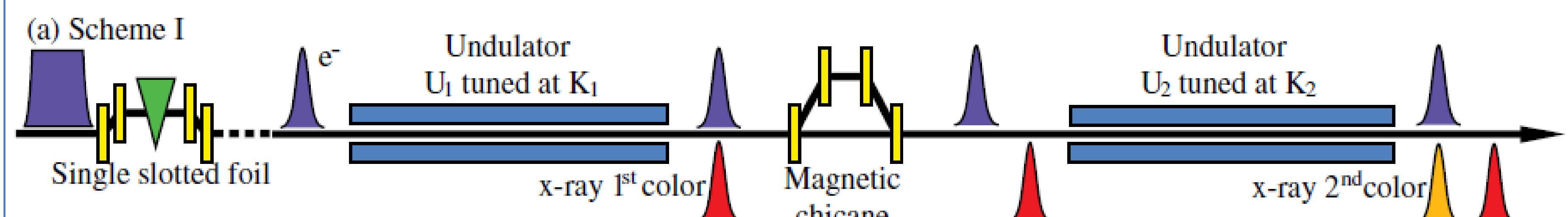
$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$



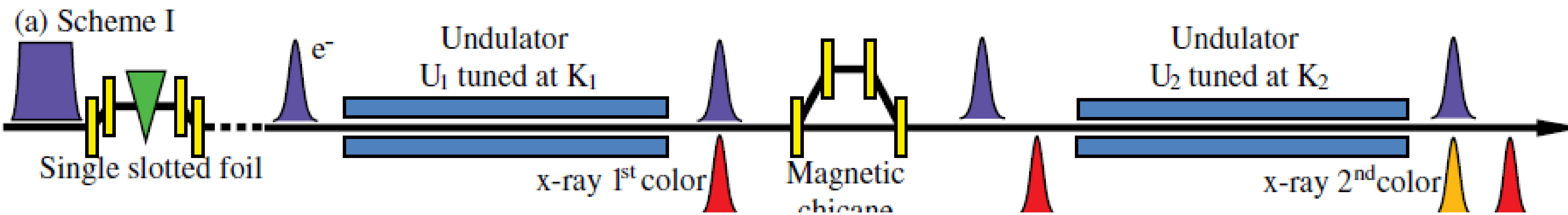
$$\lambda = \lambda_w \frac{1+K^2}{2\gamma^2}$$

Two-color FELs fall into two different categories…

$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$



Split Undulator Scheme



$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

PRL **110,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 13 December 2012; published 25 March 2013)

Split undulator in 2 parts.

Use magnetic chicane to introduce delay

Easy to tune!

~1/10 to 1/5 of SASE power

ARTICLE

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Two-colour hard X-ray free-electron laser with wide tunability

Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], Tadashi Togashi[2], Kazuaki Togawa[1], Kensuke Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

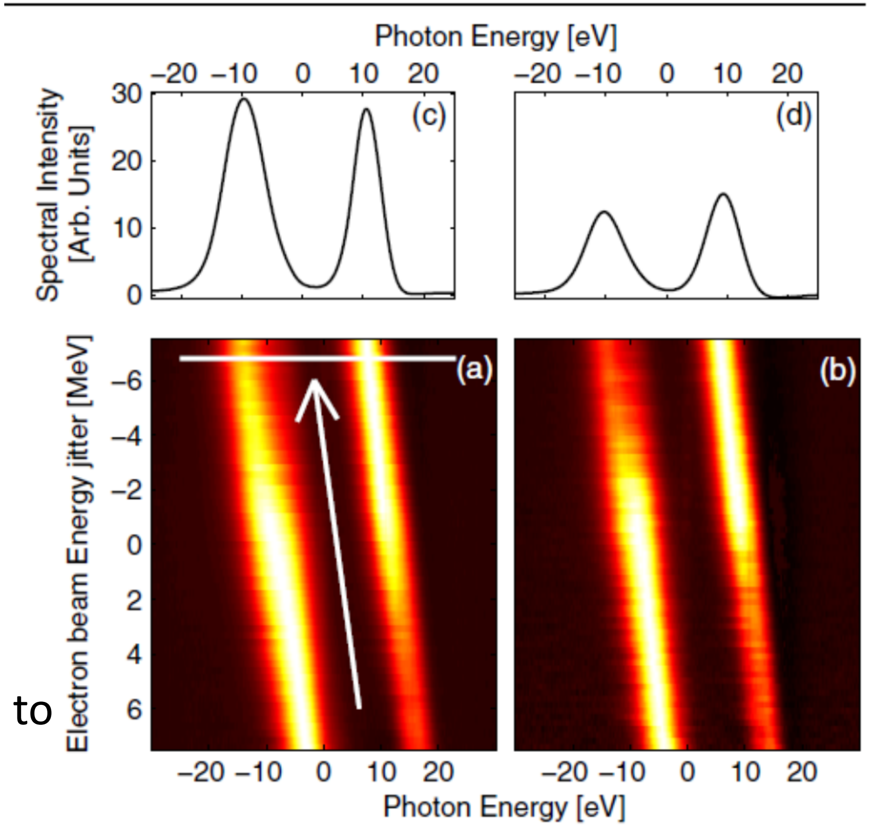
Split Undulator Scheme

Max delay:
50 fs (limited by chicane)

Can use the SXRSS chicane:
800 fs but limited pump power

Energy separation
0-3%
Limited by undulator tunability

(much larger energy separation at SACLA thanks to variable gap)



Limiting Factors

$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

1) In either scheme both colors emitted by one bunch:
CAN'T REACH SATURATION!

2) Each color uses half undulator:
At HXR pulse energy is limited to ~100 μJ

How Can We Improve?

SLAC

$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

If we generate a beam with two energy bands and send it down the undulator:

1) Each color can saturate

2) Each color uses the whole undulator (improvement by a factor ~ 20 at HXR!)

How Can We Improve?

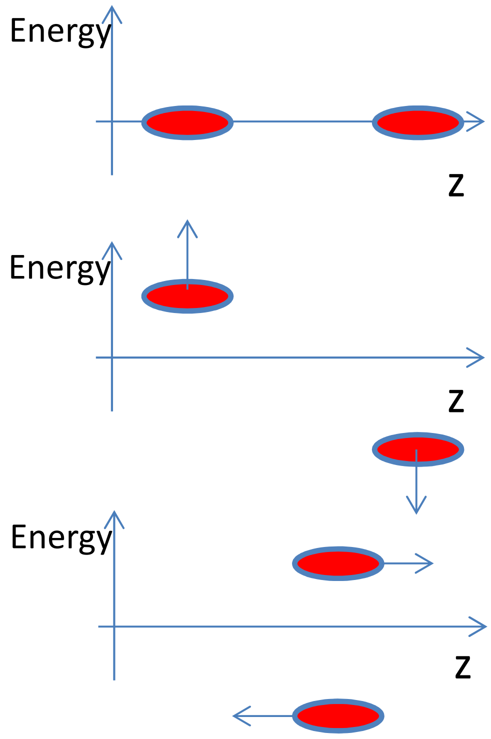
$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

If we generate a beam with two energy bands and send it down the undulator:

1) Each color can saturate

2) Each color uses the whole undulator (improvement by a factor ~ 20 at HXR!)

TWIN BUNCHES!



Generate two identical bunches with ~ps separation

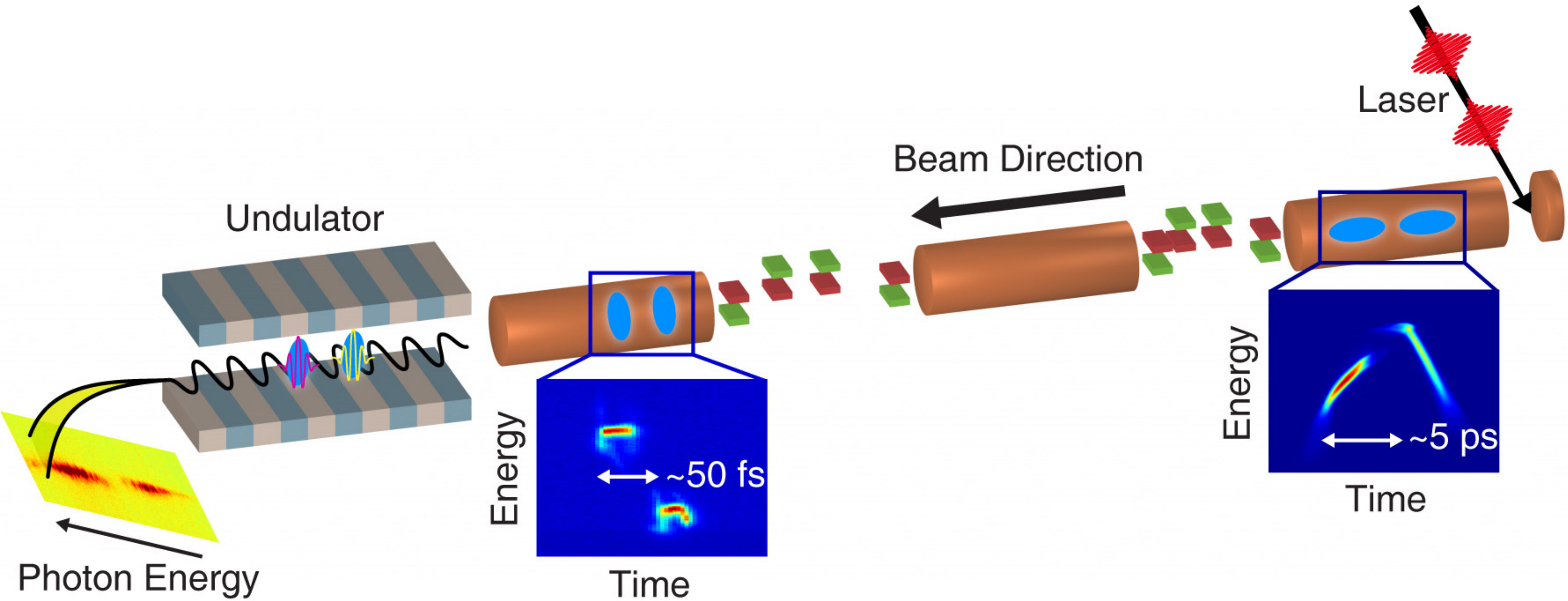
Accelerate off-crest

Superimpose them in time with dispersive transport ~fs separation

Twin Bunches!

And more on the way…

Twin-Bunch FEL



ARTICLE

Received 16 Oct 2014 | Accepted 22 Jan 2015 | Published xx xxx 2015

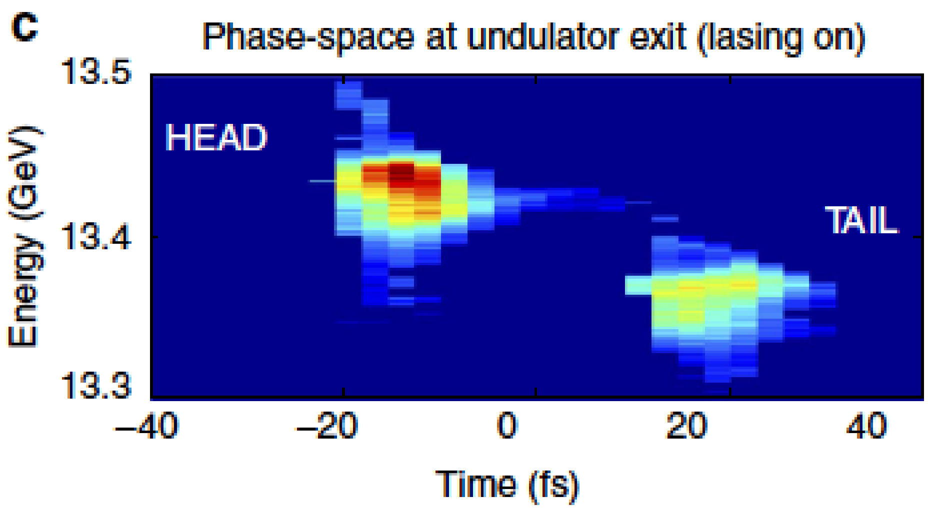
DOI: 10.1038/ncomms7369

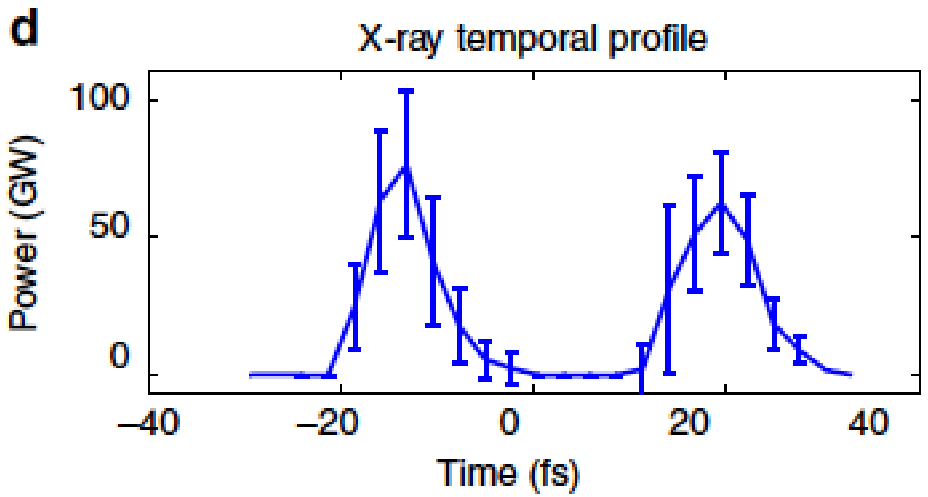
OPEN

High-intensity double-pulse X-ray free-electron laser

A. Marinelli[1], D. Ratner[1], A.A. Lutman[1], J. Turner[1], J. Welch[1], F.-J. Decker[1], H. Loos[1], C. Behrens[1,2], S. Gilevich[1], A.A. Miahnahri[1], S. Vetter[1], T.J. Maxwell[1], Y. Ding[1], R. Coffee[1], S. Wakatsuki[1,3] & Z. Huang[1]

Lasing





Peak power ~ 60 GW

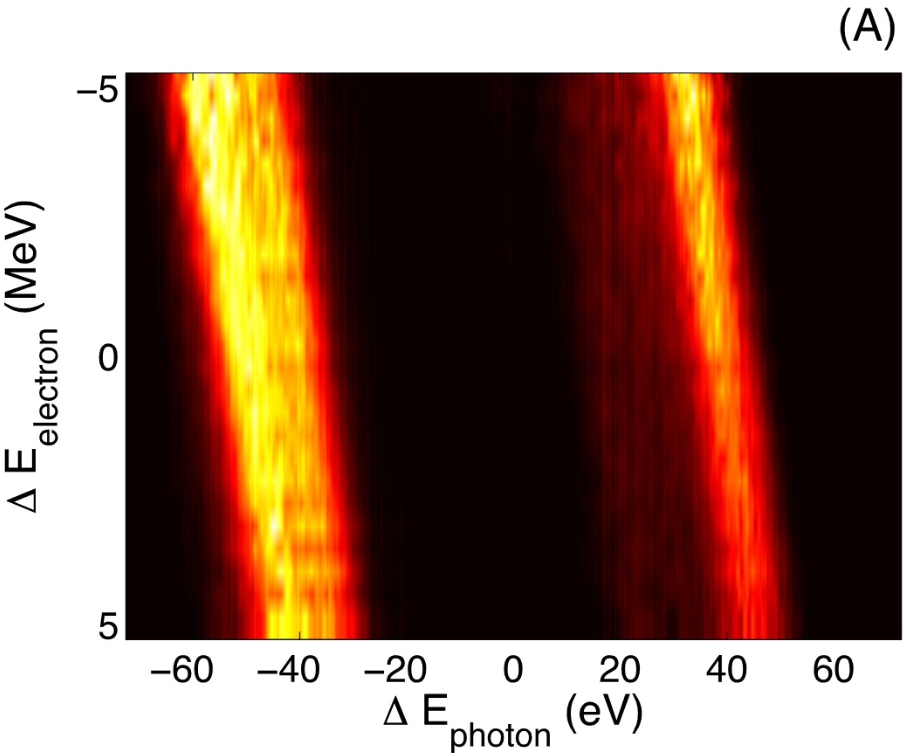
Time separation
ΔT = 35 fs

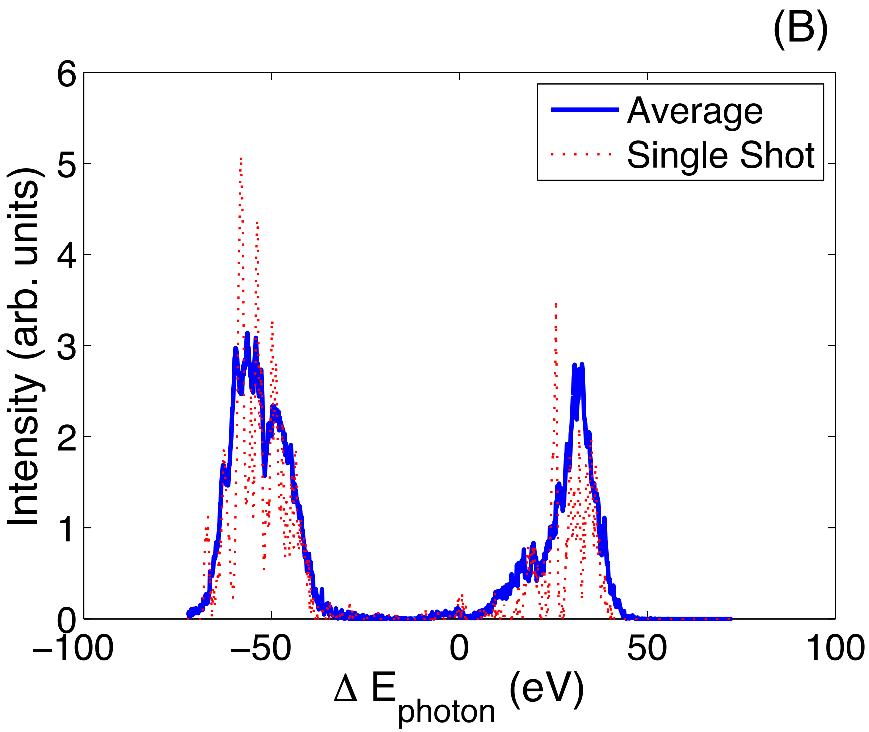
Individual duration
dT = 10 fs

E_{pulse} = 1.2 mJ

IMPROVEMENT OF 1 ORDER OF MAGNITUDE OVER STATE OF THE ART @HXR

Spectral Properties





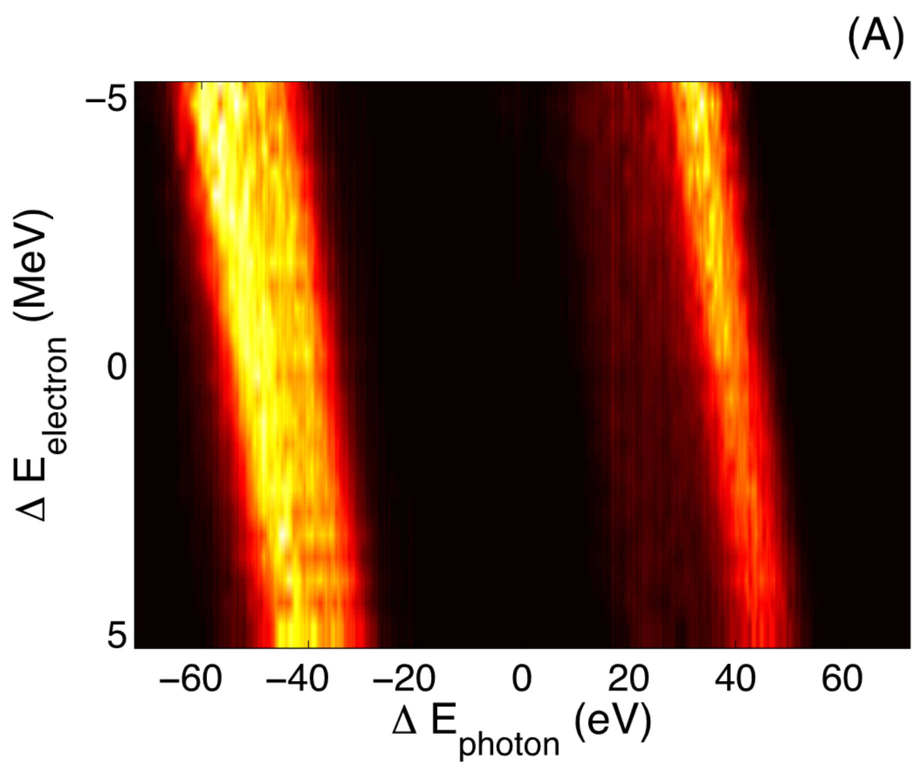
Max separation:
1% at HXR

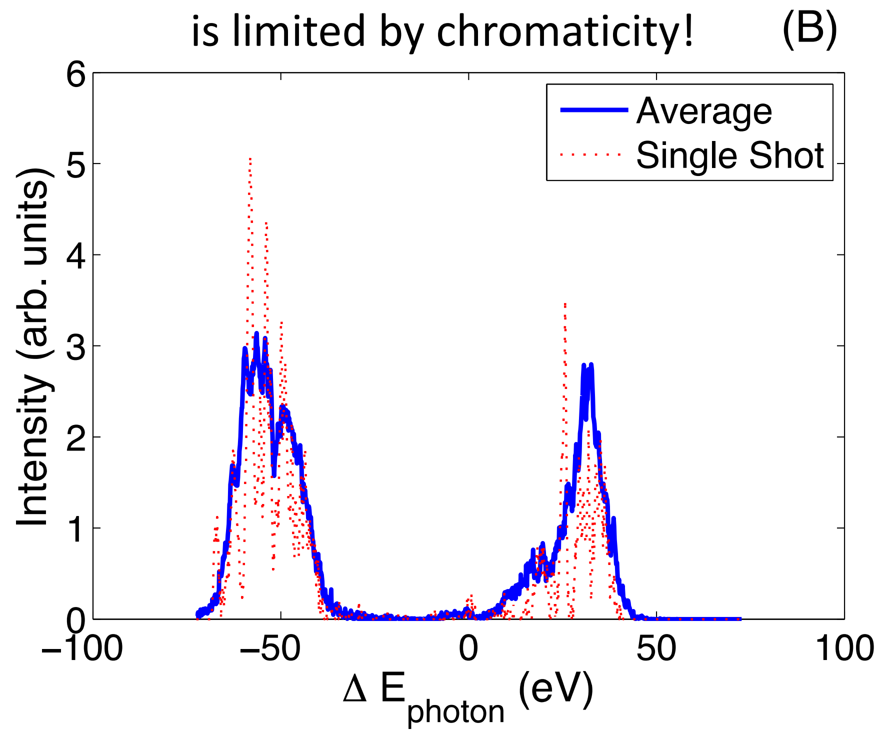
3% at SXR

90 eV Separation
10-15 eV bandwidth

Spectral Properties

NOTE: Unlike single bunch schemes, max separation is limited by chromaticity!



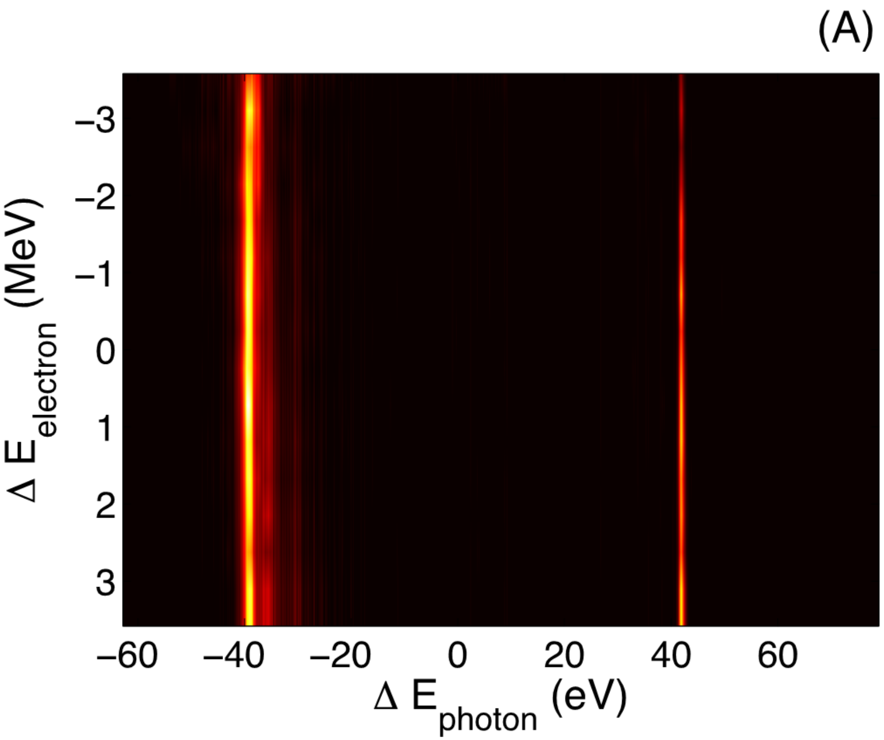


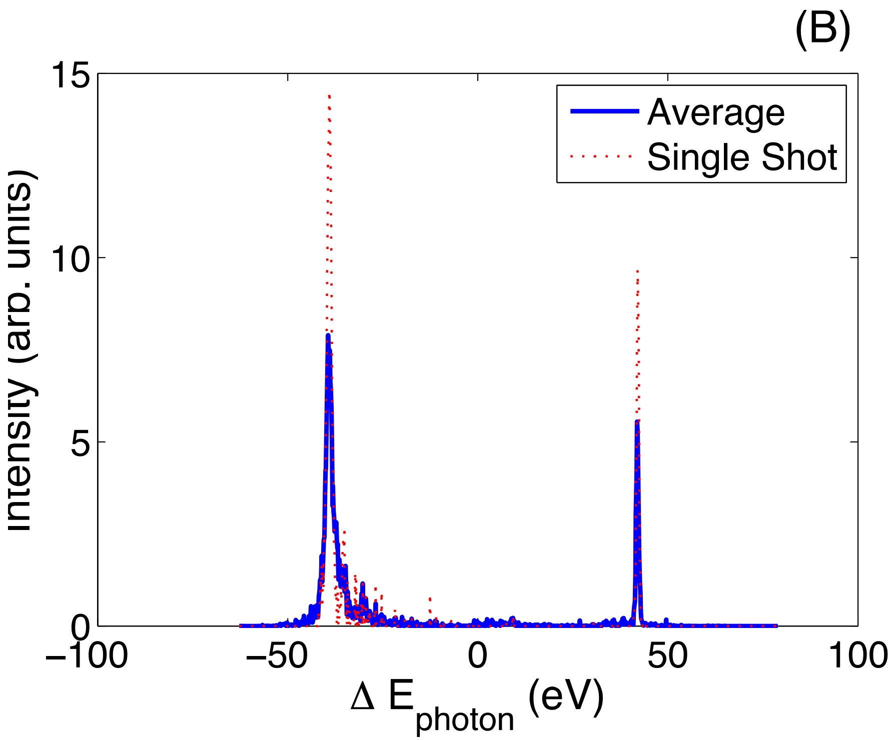
Max separation:
1% at HXR

3% at SXR

90 eV Separation
10-15 eV bandwidth

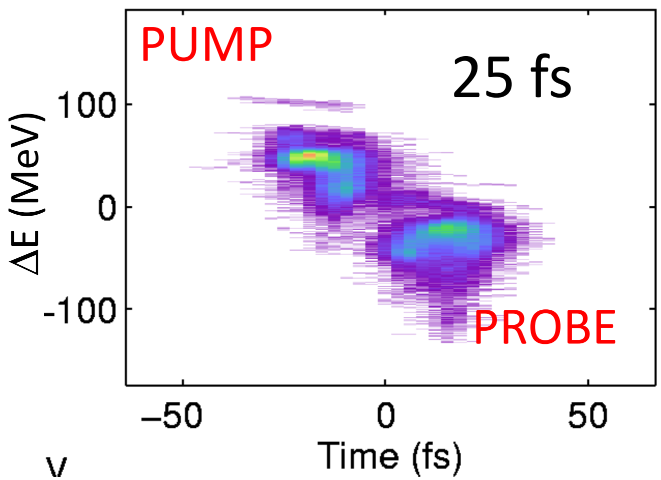
Twin-Bunch Seeded Spectra

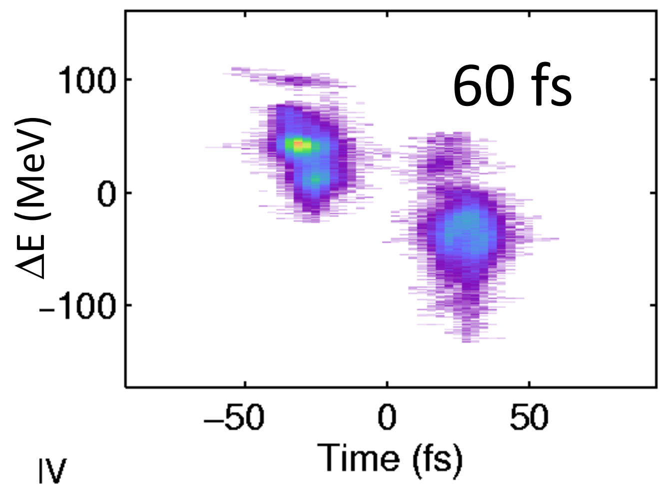


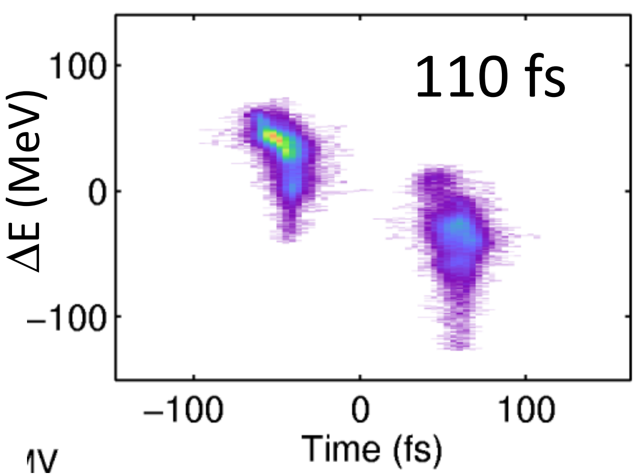


Pulse energy down to 130 uJ
Spectral brigthness x 2!

Time Delay Control







$$\Delta T_{final} = \frac{\Delta T_{initial}}{C_{factor}} + \Delta T_{GAP} \times \frac{1}{E}\frac{dE}{dt}_{wakes} \times \frac{R56}{c}$$

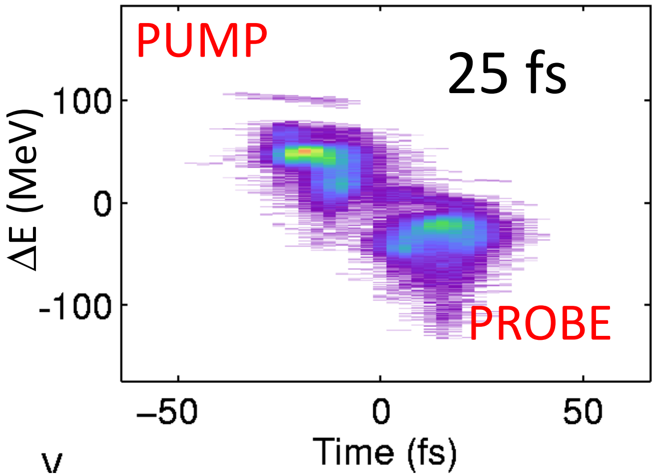
Wakefield induced delay

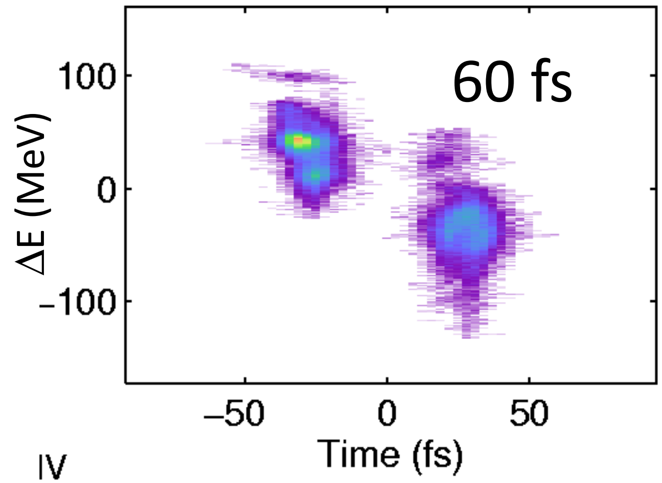
Depends on:

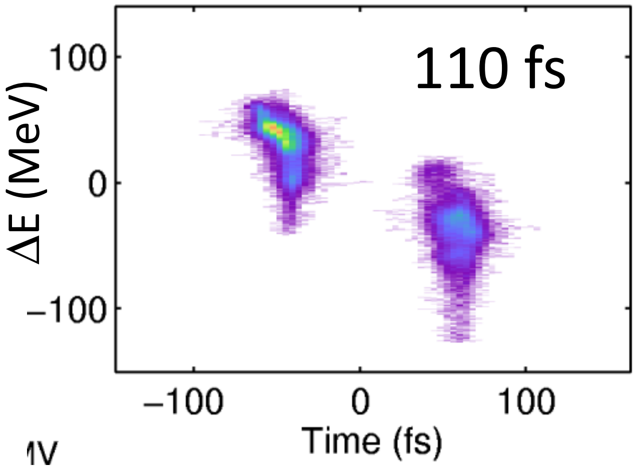
1) Cathode delay
2) BC2 dispersion

Varying both parameters achieve 10-125 fs delay

Time Delay Control







$$\Delta T_{final} = \frac{\Delta T_{initial}}{C_{factor}} + \Delta T_{GAP} \times \frac{1}{E}\frac{dE}{dt}_{wakes} \times \frac{R56}{c}$$

Wakefield induced delay

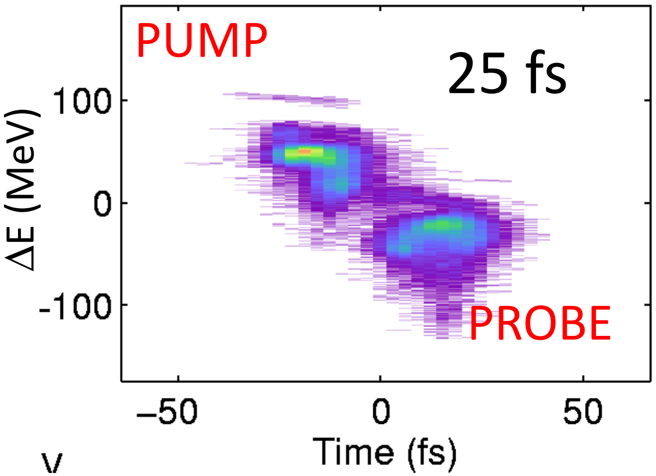
Depends on:

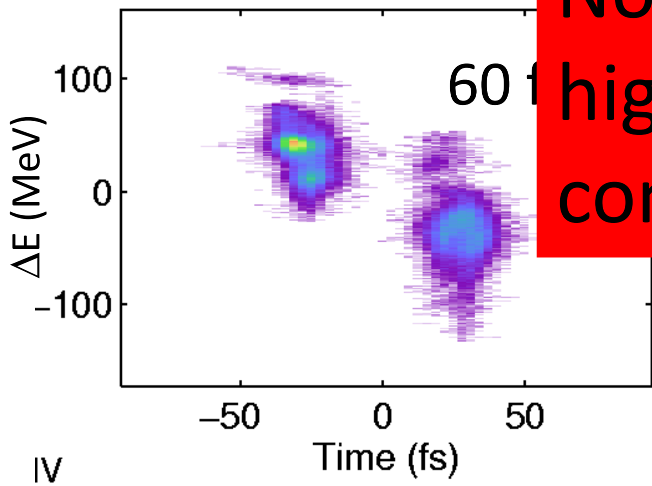
1) Cathode delay
2) BC2 dispersion

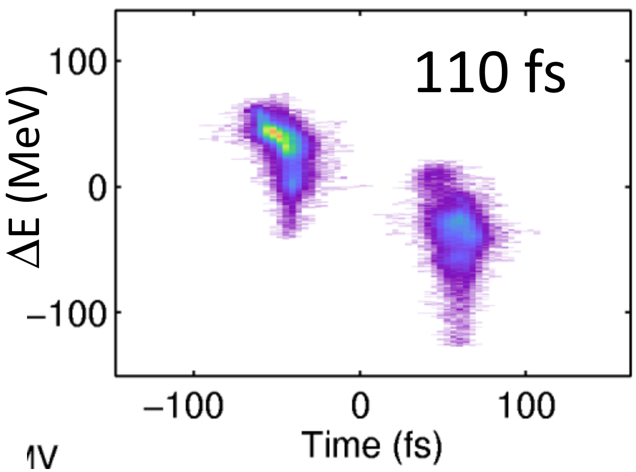
Varying both parameters achieve up to 125 fs delay

Time Delay Control

Note: at HXR high energy comes first







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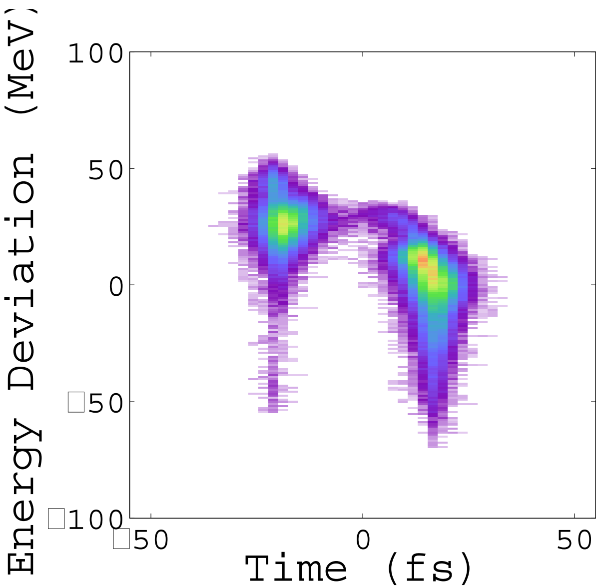
Wakefield induced delay

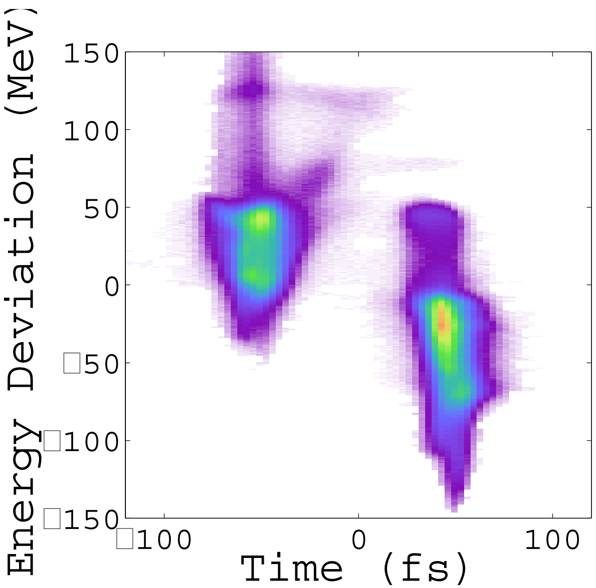
Depends on:

1) Cathode delay
2) BC2 dispersion

Varying both parameters achieve up to 125 fs delay

New Working Points

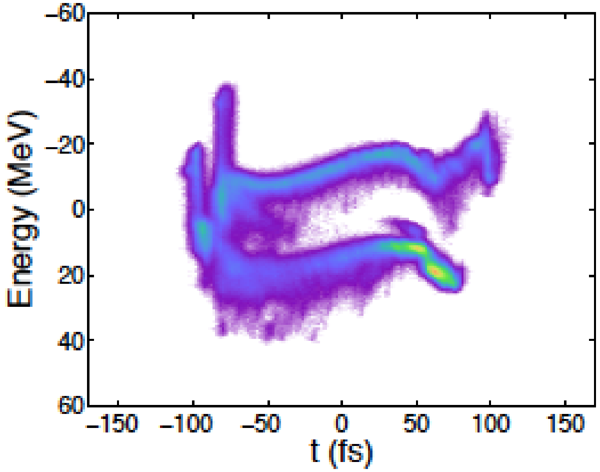


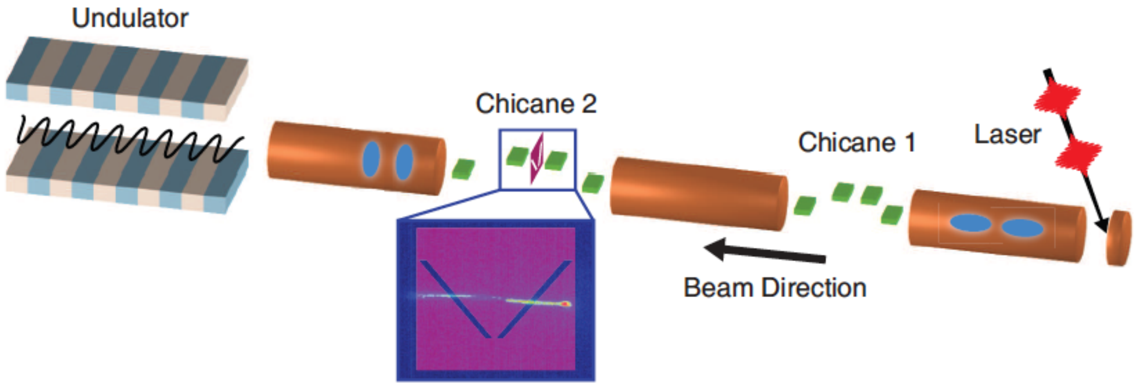


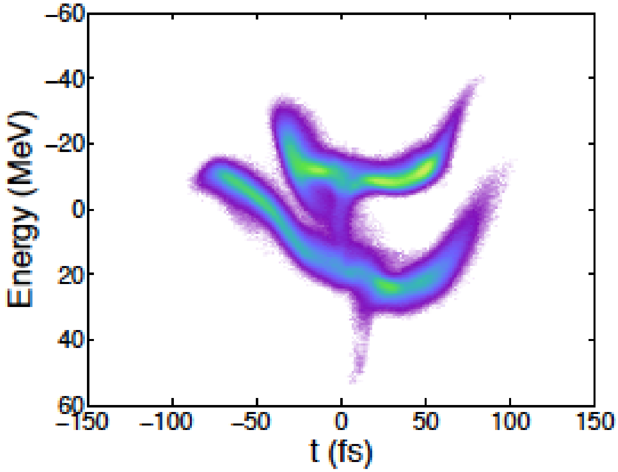
20 pC/bunch
400 uJ Pulse Energy
5-10 fs Pulse Duration

150 pC/bunch
2.3 mJ Pulse Energy
~25 fs Pulse Duration

Twin-Bunch Carving for Operation at SXR







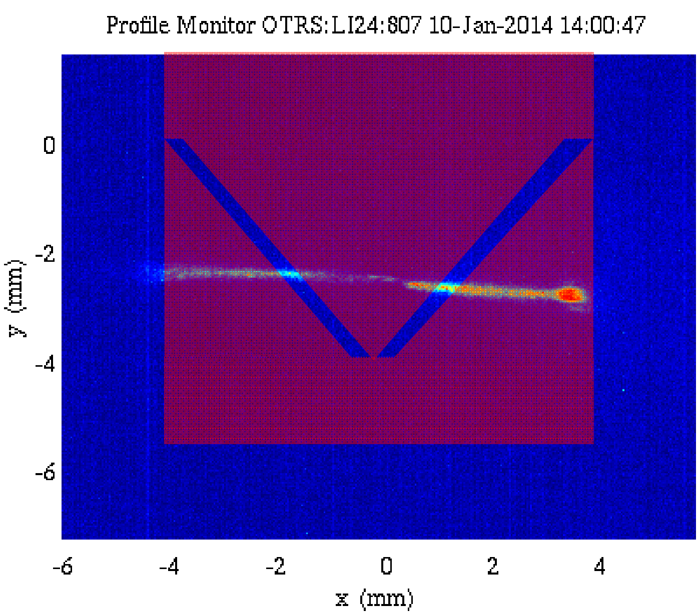
Carve out 2 short pulses out of two long bunches.

~6-7 fs FWHM
~100 uJ pulse energy

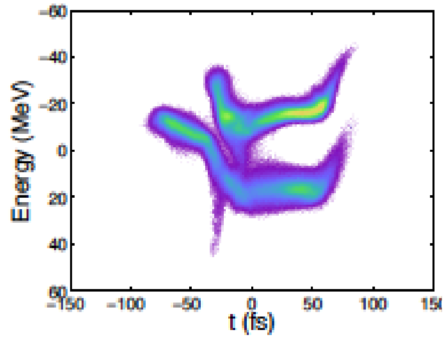
SXR Twin-Bunch: Beam Carving

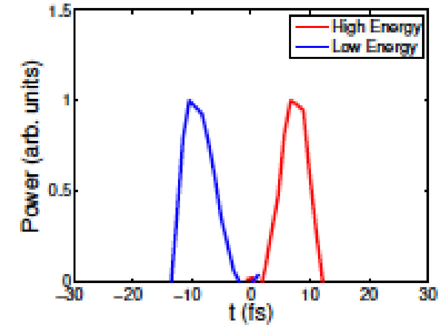
Time delay variation by scanning vertical position of foil

SCAN SMOOTHLY THROUGH 0!



X-Y distribution in BC2





SXR Twin-Bunch: Beam Carving

Time delay variation by scanning vertical position of foil

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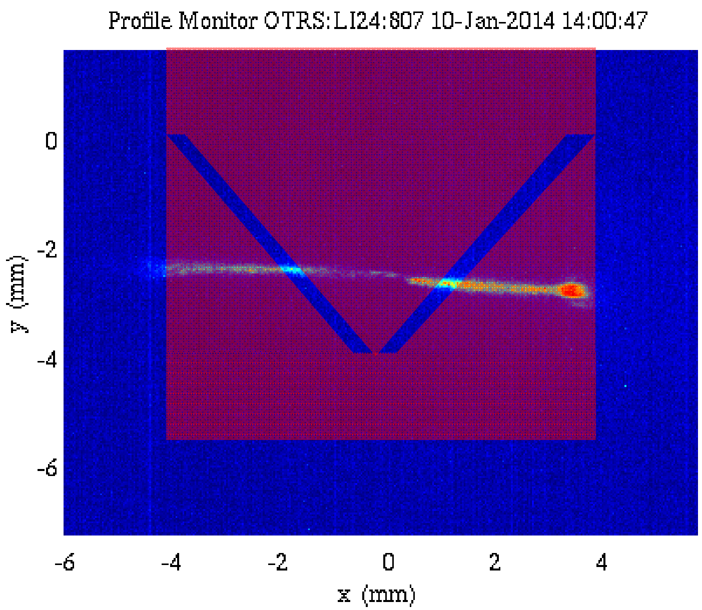
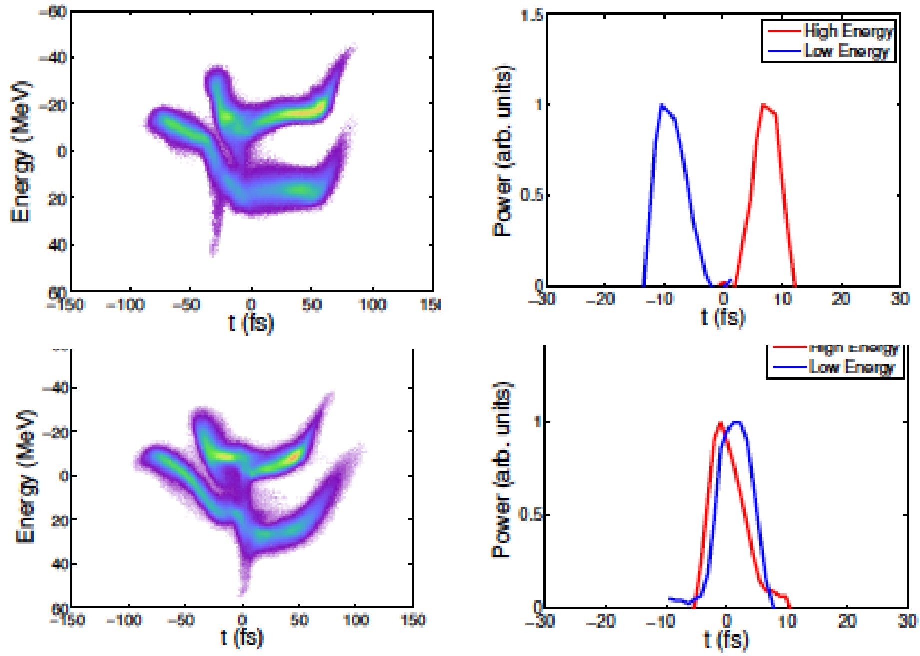


X-Y distribution in BC2



SXR Twin-Bunch: Beam Carving

Time delay variation by scanning vertical position of foil

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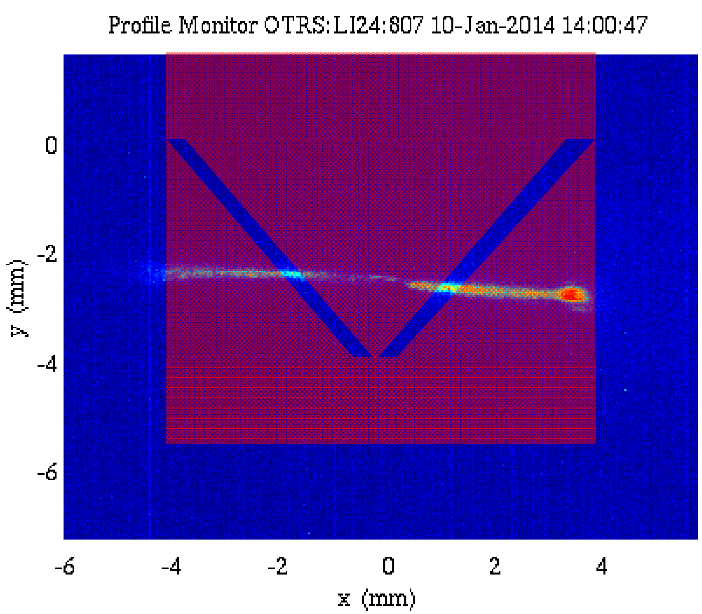
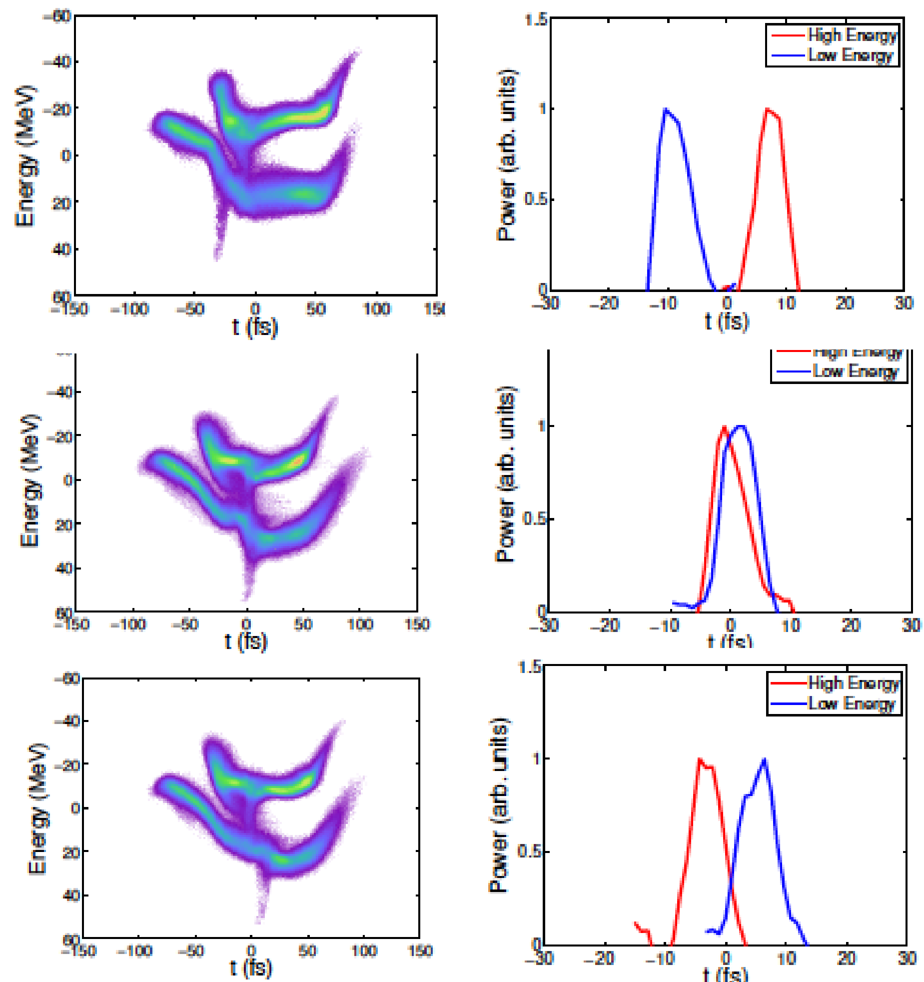
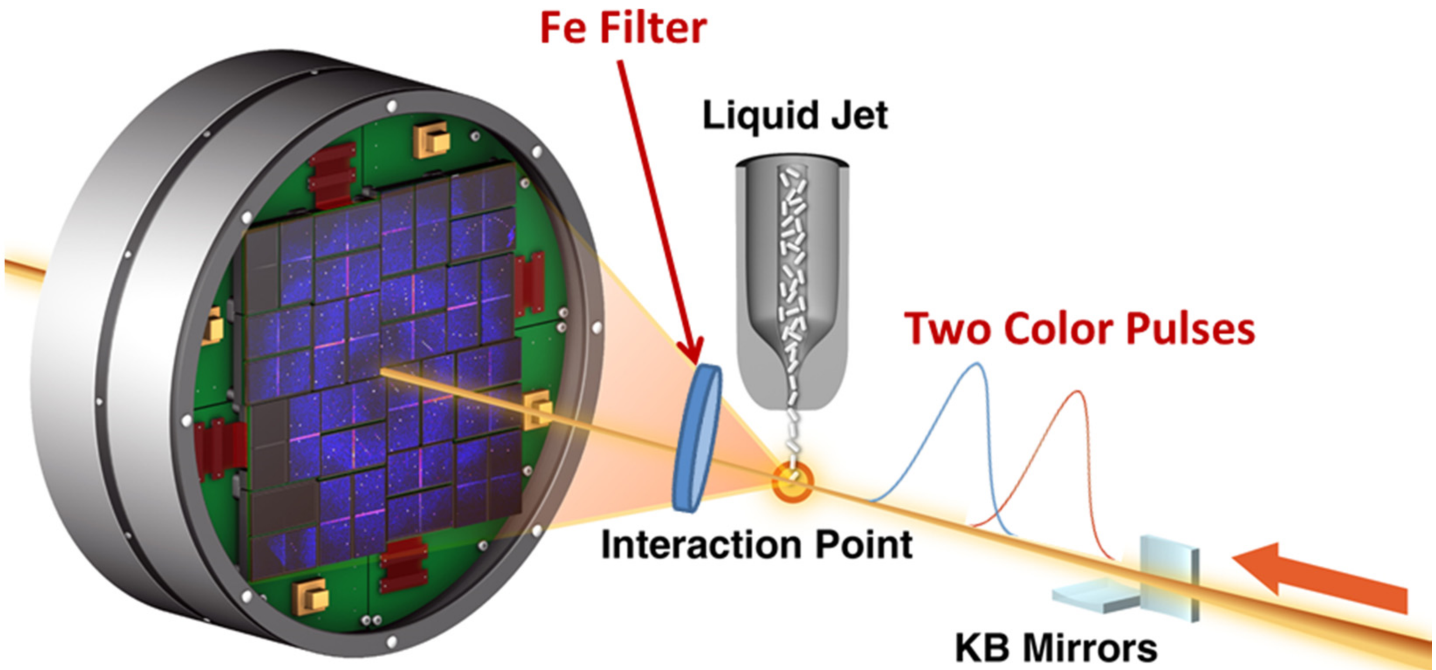


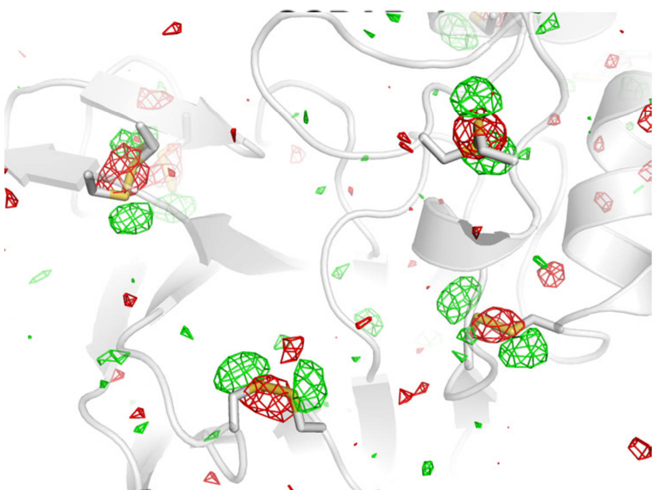
X-Y distribution in BC2



Imaging Molecular Damage at the fs Time-Scale



Courtesy of S. Boutet



Thaumatin Molecule

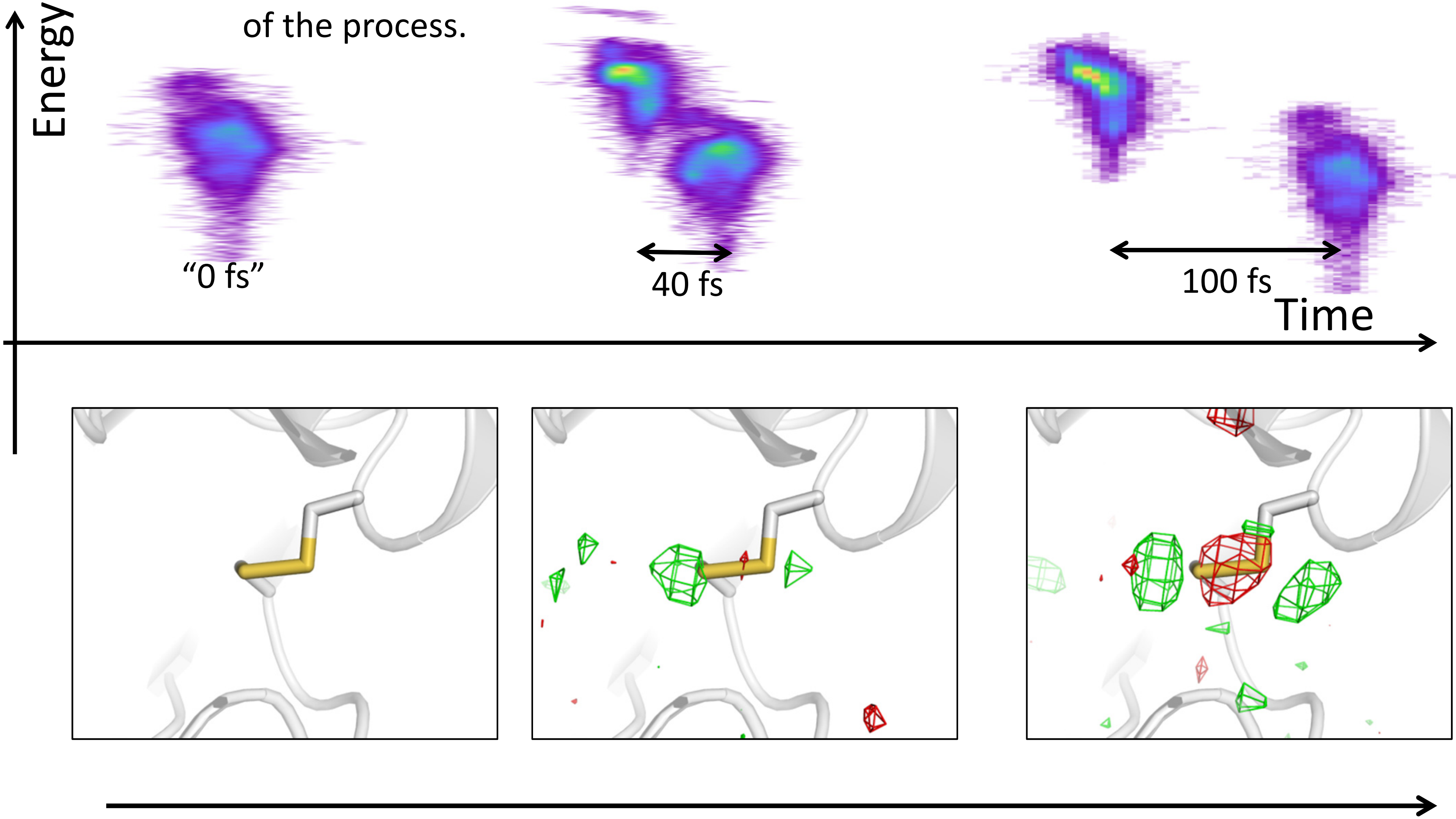
Difference between unperturbed sample and pump-probe (100 fs delay).

Green: positive electron density

Red: negative electron density

Movie of Molecular Explosion

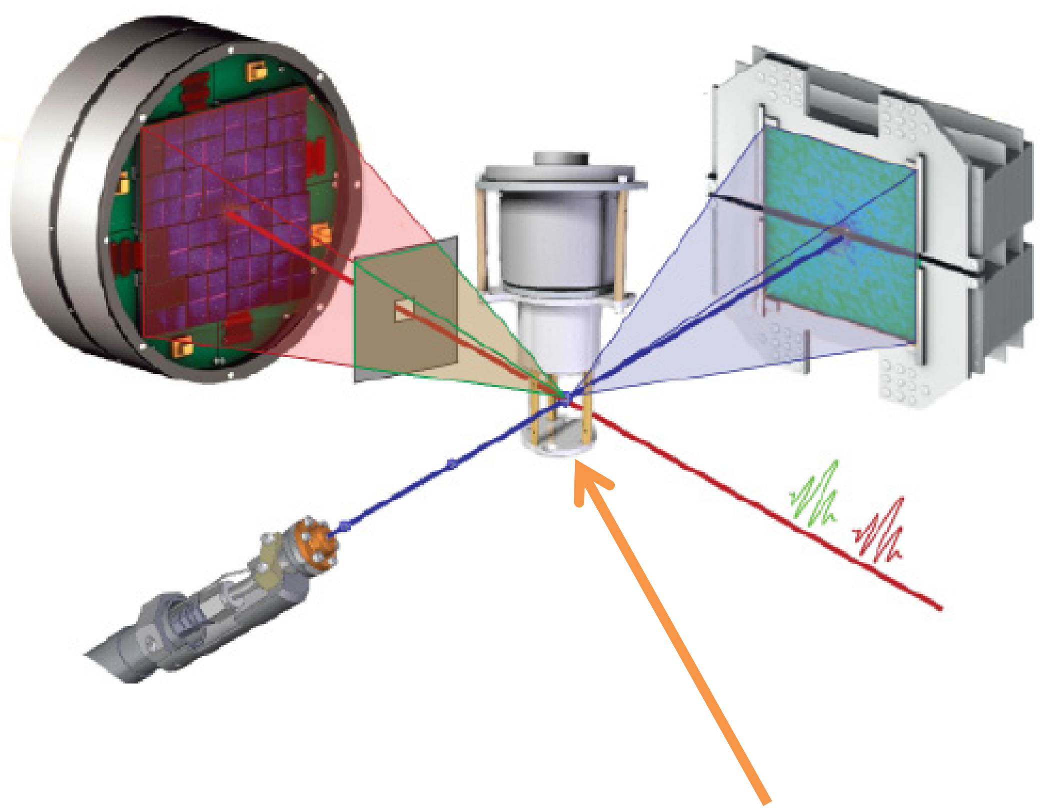
Vary time-delay to make a "movie" of the process.



Pump-probe time delay

Courtesy of S. Boutet

Femtosecond Dynamics in X-Ray Induced Nanoplasmas



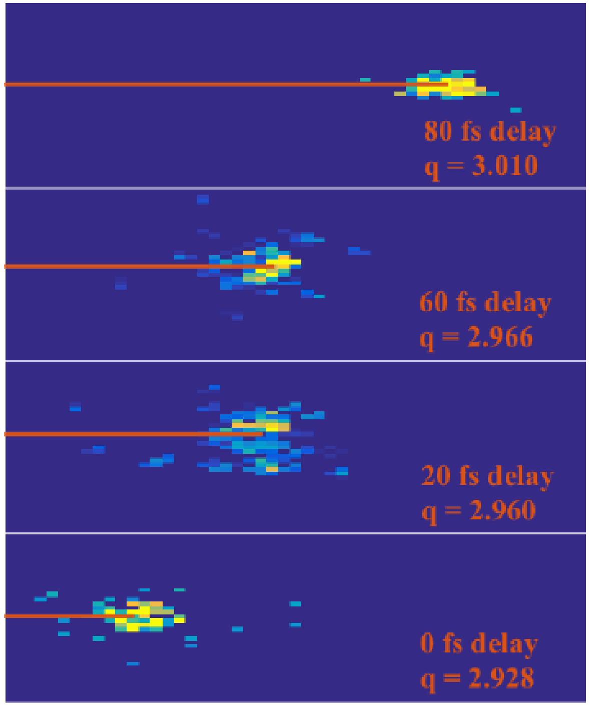
Xenon clusters

First X-ray pulse ionizes cluster:
high-temperature and pressure conditions

Probe pulse used to study ensuing dynamics

fs Dynamics in X-Ray Induced Nanoplasmas

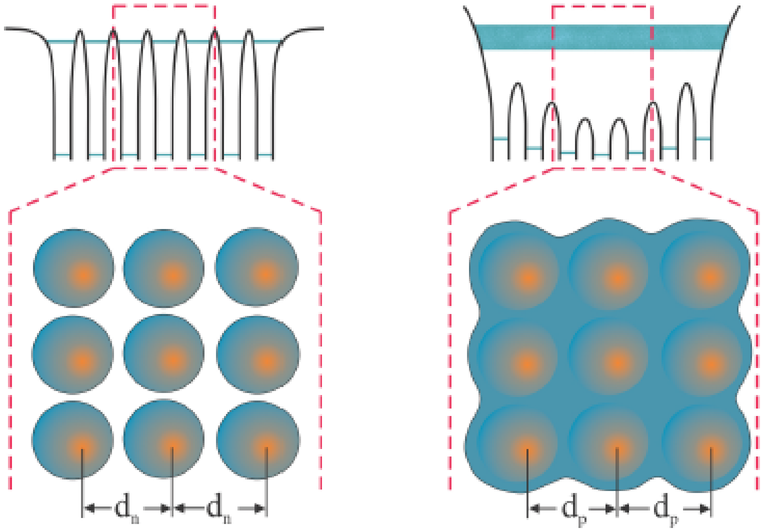
SLAC



Crystal lattice experiences unexpected COMPRESSION at the 100 fs time-scale!

Increased electron mobility induces transient metallic bond!

K. Ferguson et al.
Science Advances
29 Jan 2016:
Vol. 2, no. 1, e1500837



Courtesy of K. Ferguson

Summary

-Many two color schemes are now operational at LCLS.

-Twin-bunch preferred option at hard x-rays due to high intensity gain.

-Twin-bunch allows simultaneous self-seeding on both colors with single crystal monochromator.

-Routinely (and successfully) delivered to user experiments.

Acknowledgements

D. Ratner, Z. Huang, A. Lutman, F. J. Decker, J. Turner, Y. Ding, R. Coffee, S. Gilevich, S. Vetter, F. Zhou, H. Loos, T. Maxwell, C. Behrens

For their help designing and performing this experiment.

The entire Accerator Operations Group, in particular M. Gibbs, E. Tse, A. Egger, H. Smith, L. Alsberg, B. Ripman and D. Sanzone for their support during the experimental demonstration and user delivery.

S. Wakatsuki, K. Ferguson, C. Bostedt and B. Barbrel for useful discussions and suggestions.